

## Top Quark Mass Measurements

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The top quark, with its extraordinarily large mass (nearly that of a gold atom), plays a significant role in the phenomenology of EWSB in the Standard Model. In particular, the top quark mass when combined with the  $W$  mass constrains the mass of the as yet unobserved Higgs boson. Thus, a precise determination of the mass of the top quark is a principal goal of the CDF and DØ experiments. With the data collected thus far in Runs 1 and 2 of the Tevatron, CDF and DØ have measured the top quark mass in both the lepton+jets and dilepton decay channels using a variety of complementary experimental techniques. I present an overview of the most recent of the measurements.

### 1 Introduction

The top quark was discovered by the CDF and DØ collaborations in 1995 using  $\sim 110 \text{ pb}^{-1}$  of  $p\bar{p}$  collisions at  $\sqrt{s} = 1.8 \text{ TeV}$  recorded during Run 1 of the Tevatron.<sup>1,2</sup> These data were also used to make direct measurements of the mass of the top quark.<sup>3,4</sup> After substantial upgrades to both the experimental detectors and the accelerator complex, Run 2 of the Tevatron began in 2001. To date, the DØ and CDF experiments have recorded  $\sim 0.5 \text{ fb}^{-1}$  of  $p\bar{p}$  collisions at  $\sqrt{s} = 1.96 \text{ TeV}$ , of which  $\sim 160 \text{ pb}^{-1}$  have been analyzed for the results presented here.

The mass of the top quark is a fundamental parameter of the Standard Model (SM) of particle physics. Moreover, owing to its large relative value, the top quark's mass is especially important in the phenomenology of the SM. In particular, through loop corrections to the mass of the  $W$  boson, the value of the top quark mass logarithmically effects the mass of the elusive Higgs boson. Precise determinations of the  $m_t$  therefore constrain the allowable values of  $m_H$ .

Top quarks are pair-produced in Run 2 of the Tevatron through quark-antiquark annihilation (85%) and gluon-fusion (15%) processes. Each top quark decays before hadronizing via the reaction  $t \rightarrow bW$ . Events are classified by the subsequent decay channel of the  $W$ . The mode where one  $W$  has decayed hadronically and the other has decayed leptonically ( $e$  or  $\mu$  only) is called “lepton+jets” and has a branching fraction of 30%. The mode where both  $W$ 's have decayed leptonically is called “dilepton” and has a branching fraction of 5%. The mode where both  $W$ 's have decayed hadronically is called “all jets” and has a branching fraction of 44%. The remainder of the branching fraction (21%) involves one or more  $W \rightarrow \tau\nu$  decays.

The experimental signature of a  $t\bar{t}$  event is thus the presence of two high  $E_T$   $b$  quark jets (identifiable by a displaced secondary vertex, called a “b-tag”) with additional energetic light quark jets and/or leptons depending on the decay mode. For leptonic modes there will also be significant missing transverse energy due to the unobserved neutrinos. There may also be additional jets due to initial or final state gluon radiation.

Reconstruction of the top quark’s invariant mass presents several experimental challenges. First, at a hadron collider, only the transverse component of the missing energy can be detected so the longitudinal component of any neutrino’s momentum is unknown which results in an ambiguity in  $m_t$ . Second, since jets are detected and not their originating quarks, measured jet energies must be corrected back to the parton-level (called the “jet-energy scale”). Finally, in performing the reconstruction a jet-parton assignment must be made of which there will in general be many possible permutations.

## 2 DØ Run I Matrix Element Top Quark Mass Measurement

The DØ Collaboration has recently measured the top quark mass to be  $180.1 \pm 5.4 \text{ GeV}/c^2$  by re-analyzing their Run 1 b-tagged lepton+jets top sample with an analysis technique designed to extract maximal event information.<sup>6</sup> The precision of the DØ ME measurement alone is equal to that of all previous measurements combined and dominates the current world average<sup>7</sup> of  $178.0 \pm 4.3 \text{ GeV}/c^2$ .

This measurement employs a “matrix element” (ME) technique whereby a parameter  $\alpha$  (in this case  $m_t$ ) is estimated from a sample of  $N$  events by maximizing a likelihood given by

$$\mathcal{L}(\alpha) = e^{-N \int \bar{P}(x;\alpha) dx} \prod_{i=1}^N \bar{P}(x_i; \alpha) \quad (1)$$

where  $x_i$  is a set of measured observables and  $\bar{P}(x; \alpha)$  is obtained from the differential cross-section for the process under study (*i.e.*  $p\bar{p} \rightarrow t\bar{t}$ ) as follows:

$$\bar{P}(x; \alpha) = \frac{1}{\sigma} \int d^n \sigma(y; \alpha) dq_1 dq_2 f(q_1) f(q_2) \mathcal{W}(x, y) \quad (2)$$

where  $\sigma$  is the cross-section in question,  $f(q_i)$  are parton distribution functions (PDFs) and  $\mathcal{W}$  is a “transfer” function that relates parton-level quantities to their observable counterparts. Background processes are explicitly included in the likelihood with appropriate weights. Thus, for  $k-1$  backgrounds the likelihood is modified as

$$\bar{P}(x; c_1, \dots, c_k, \alpha) = \sum_{i=1}^k c_i \bar{P}_i(x; \alpha) \quad (3)$$

## 3 CDF Run 2 Top Quark Mass Measurements

### 3.1 Dynamic Likelihood Method

CDF has measured the top quark mass in the b-tagged lepton+jets channel using a ME technique similar to that employed by DØ which it calls the “Dynamic Likelihood Method (DLM).<sup>8</sup> In this method, the likelihood for the  $i^{th}$  event is defined, for a given top mass by

$$\mathcal{L}_i(m_t) = \sum_{I_t} \sum_{I_s} \int \frac{2\pi^4}{Flux} F(z_a, z_b) f(p_T) |\mathcal{M}|^2 \mathcal{W}(I_t, \mathbf{x}|\mathbf{y}; m_t) d\mathbf{x} \quad (4)$$

where analogous to Equation 2,  $\mathcal{M}$  is the ME in question,  $F(z_i)$  are PDFs and  $\mathcal{W}$  is a the CDF transfer function. Unlike the DØ ME analysis, DLM does not incorporate the background into the likelihood but employs a mapping function instead. After event selection, 22  $t\bar{t}$  candidates remain with an estimated background of  $4.2 \pm 1.2$ . With this sample, the above likelihood is

maximized and a top quark mass of  $177.8^{+4.5}_{-5.0} \pm 6.2$  is extracted. This measurement is systematic limited by the jet energy scale uncertainty.

### 3.2 Template Method

CDF has performed another top mass measurement with the tagged lepton+jets sample using a strategy based on that which was used in the more traditional Run 1 measurements. This method reconstructs the invariant mass of the top in each event and computes the following expression

$$\chi^2 = \sum_{\ell, jets} \frac{(\hat{P}_T - P_T)^2}{\sigma_{P_T}^2} + \sum_{x,y} \frac{(\hat{U}_i - U_i)^2}{\sigma_U^2} + \frac{(M_{jj} - M_W)^2}{\Gamma_W^2} + \frac{(M_{\ell\nu} - M_W)^2}{\Gamma_W^2} + \frac{(M_{bjj} - M_t)^2}{\Gamma_t^2} + \frac{(M_{b\ell\nu} - M_t)^2}{\Gamma_t^2} \quad (5)$$

for the two neutrino solutions and all parton assignment permutations. This procedure is performed on signal and background Monte Carlo samples and the reconstructed mass with the smallest  $\chi^2$  is histogrammed forming templates which are then used to fit 28  $t\bar{t}$  candidate events using an unbinned likelihood as shown in Figure 1. This analysis yields a measured top mass of  $174.9^{+7.1}_{-7.0} \pm 6.5$ .

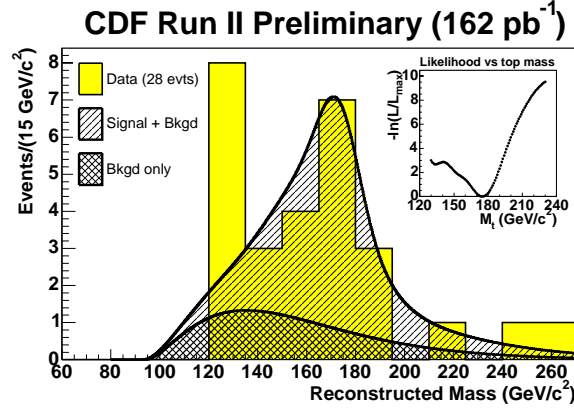


Figure 1: CDF measurement of top quark mass in lepton+jets channel using template technique to analyze of Run 2 data.

### 3.3 Multivariate Template Method

CDF has also performed another lepton+jet analysis which attempts to improve on the Run 1 template technique in several ways: multivariate templates are used, *in situ* jet energy calibration is performed using the hadronic  $W$  decay, and kinematic variables are used to estimate the probability that the best  $\chi^2$  resulted from a correct jet-parton assignment. The resulting top mass when this method is applied to 33 candidate events candidates selected from CDF Run 2 data is  $179.6^{+6.4}_{-6.3} \pm 6.8$ .

### 3.4 Other CDF Run 2 Top Mass Measurements

Finally, CDF has performed complementary Run 2 measurements of the top quark mass using the non-tagged lepton + jets and dilepton samples. These measurements while less precise on

their own will serve to reduce the overall uncertainty on the top mass when combined with the other results.

## 4 Summary and Future Outlook

There has been substantial recent progress in top quark mass measurements with a steady stream of new measurements being produced by the CDF and DØ experiments. A summary of these measurements is presented in Figure 2. Combinations of these measurements across decay modes and between the two experiments can be expected soon. These analyses are fast becoming systematic limited. The challenge to usher in the the era of precision  $m_t$  measurements will be the reduction of the jet-energy scale systematic uncertainty.

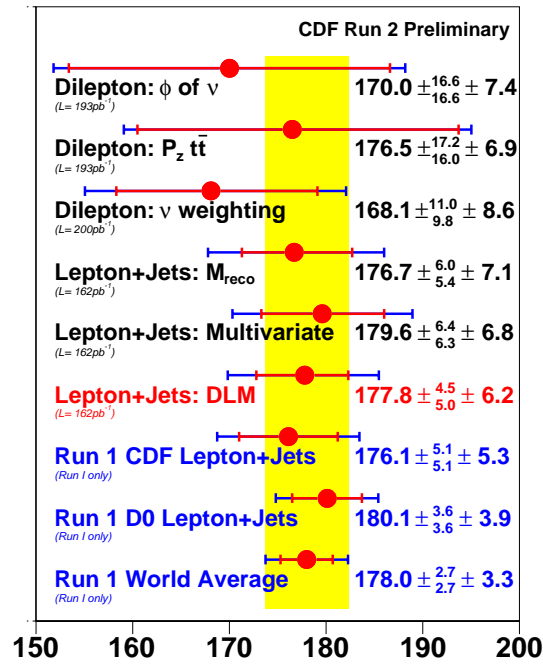


Figure 2: Summary of CDF and DØ top quark mass measurements.

## References

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